

Spiral exchange interaction in diluted magnetic semiconductor junction

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(Received 11 November 2003; accepted 19 February 2004)

We studied the exchange interactions mediated by polarized itinerant carriers in diluted magnetic semiconductor (DMS) junction. In contrast to the ordinary Ruderman–Kittel–Kasuya–Yosida oscillations, the induced moment possesses an interesting spiral motion, accompanied by angular oscillations. The spiral motion remains robust in the entire $T < T_c$ regime while the oscillatory motion gets enhanced as $T \rightarrow T_c$. To explore the phenomena, it is proposed that a ferromagnet/DMS/ferromagnet junction would bring out interesting spin-dependent transport properties and possible applications in spintronics. © 2004 American Institute of Physics.
[DOI: 10.1063/1.1705725]

One of the key elements in spintronics is the diluted magnetic semiconductor (DMS), which incorporates both charge and spin phenomena together in one material.^{1,2} With rapid and intensive research attention, robust ferromagnetic order was demonstrated in $(\text{Ga}_{1-x}\text{Mn}_x)\text{As}$ with Currie temperature around 150 K.^{3,4} It is generally believed that the ferromagnetism in DMS is mediated by the itinerant carriers in the host semiconductor.^{5–8} For the unpolarized itinerant carriers, the mediated exchange coupling among magnetic moments is the well-known Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction. However, since itinerant carriers in DMS are polarized with sensitive temperature dependence,^{9–11} it is interesting to study what kind of exchange coupling gets generated.

In this letter, a self-consistent Green's function approach is employed to address this issue. Note that while the RKKY exchange interaction has been known for a long time, direct experimental evidence has only been detected recently.¹² An easier way is through the spin-dependent scattering in the ferromagnet/nonmagnetic metallic junction.^{13,14} Here we propose a similar experimental setup, as shown in Fig. 1, to explore the effective exchange interaction in DMS. One might expect that the effective exchange interaction mediated by itinerant carriers in DMS also exhibits similar RKKY-type behavior. However, it is found that the presence of finite polarization gives rise to qualitatively different behavior. In the ferromagnet/DMS/ferromagnet junction, the induced polarization is spiral with angle $\theta_s(d)$ depending on the width of the junction. The spatial dependence of the spiral angle at different temperatures will be studied in detail later.

The DMS is modeled by the Hamiltonian, containing the kinetic energy of the itinerant carriers and the exchange in-

teraction between itinerant carriers and the localized moments doped into the host semiconductor,

$$H = H_0 + J \int d^3r \mathbf{S}(r) \cdot \mathbf{s}(r), \quad (1)$$

where the spin density of the localized moments is $\mathbf{S}(r) = \sum_i \delta^3(r - \mathbf{R}_i) \mathbf{S}_i$ and the itinerant spin density is $\mathbf{s}(r) = \psi^\dagger(r) (\boldsymbol{\sigma}/2) \psi(r)$. The band structure of the itinerant carriers is described by the host semiconductor. Since the emphasis here is to demonstrate the qualitative difference from the usual RKKY exchange coupling, the dispersion is taken to be the simplest parabolic band $H_0 = p^2/2m^*$. Generalization to more realistic but complex band structures, such as the six-band Luttinger model, can be achieved straightforwardly. Throughout the letter, the parameters are set to the typical values in $(\text{Ga}_{1-x}\text{Mn}_x)\text{As}$: $J = 0.15 \text{ eV nm}^3$ and $m^* = 0.5m_e$. Besides, the densities of itinerant carriers and localized moments are $c^* = 0.1 \text{ nm}^{-3}$ and $c = 1 \text{ nm}^{-3}$, respectively.

The induced exchange interaction $J_{ij}(r)$ mediated by polarized itinerant carriers is directly proportional to the static spin susceptibility, $J_{ij}(r) = J^2 \chi_{ij}(r, \omega = 0)$, within the linear-response regime. The spin susceptibility is

$$\chi_{ij}(r, t) = -i\Theta(t) \langle \langle [s_i(r, t), s_j(0, 0)] \rangle \rangle, \quad (2)$$

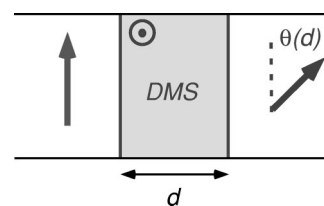


FIG. 1. Schematic diagram for a ferromagnet/DMS/ferromagnet junction. The polarization of DMS is placed in the z direction and the magnetization on the left is fixed in the y direction. The induced polarization on the right has a spiral angle $\theta(d)$ depending on the junction width d .

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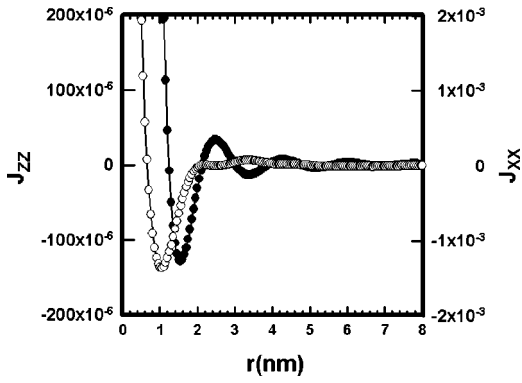


FIG. 2. The diagonal parts of exchange interactions $J_{zz}(r)$ (closed symbols) and $J_{xx}(r)$ at $T = 10$ K.

where the double angular brackets imply both thermal and quantum averages. To compute the susceptibility at finite temperature, we employed the self-consistent Green's function method developed previously^{15,16} to obtain the propagators for itinerant carriers and localized moments. With these Green's functions, the average spin densities of itinerant and localized spins, $\langle S_z \rangle$ and $\langle s_z \rangle$, can be determined self-consistently in numerics. With the particular set of parameters chosen in this letter, the Curie temperature is about $T_C \approx 45$ K.

Making use of Eq. (2) from employing equation of method on it,¹⁷ the exchange couplings generated from the diagonal parts of the spin susceptibility are

$$J_{zz}(r) = \frac{J^2 m}{4\pi^3 \hbar^2} \frac{1}{r^2} \int_0^\infty k \sin(kr) \cos(kr) (f_\uparrow + f_\downarrow) dk, \quad (3)$$

$$J^{xx}(r) = \frac{J^2 m}{4\pi^3 \hbar^2} \frac{1}{r^2} \left[\int_0^\infty k \sin(kr) \cos(\sqrt{k^2 + k_\Delta^2} r) f_\uparrow dk + \int_{k_\Delta}^\infty k \sin(kr) \cos(\sqrt{k^2 - k_\Delta^2} r) f_\uparrow dk + \int_0^{k_\Delta} k \sin(kr) e^{-\sqrt{k_\Delta^2 - k^2} r} f_\downarrow dk \right], \quad (4)$$

where $\hbar^2 k_\Delta^2 / 2m^* = \Delta$ and $\Delta = J \langle S_z \rangle$ is the effective Zeeman gap caused by the average local magnetization. The Fermi-Dirac distribution for spin-up and spin-down itinerant carriers are $f_{\uparrow, \downarrow}$, respectively.

The spatial dependencies of $J_{zz}(r)$ and $J_{xx}(r) = J_{yy}(r)$ are shown in Fig. 2. It is evident that they show oscillatory RKKY behavior and decay quickly from the origin. Note that the finite polarization causes the nonuniform decay of the oscillation amplitudes. The finite polarization also gives rise to the off-diagonal exchange interactions. It is straightforward to show that $J_{zx} = J_{zy} = 0$ from symmetry arguments. The only nonvanishing off-diagonal exchange interaction is

$$J^{xy}(r) = \frac{J^2 m}{4\pi^3 \hbar^2} \frac{1}{r^2} \int_{k_\Delta}^\infty k \sin(kr) \sin(\sqrt{k^2 - k_\Delta^2} r) f_\uparrow dk - \int_0^{k_\Delta} k \sin(kr) \sin(\sqrt{k_\Delta^2 - k^2} r) f_\downarrow dk. \quad (5)$$

It is clear that the first and second integrals cancel when the polarization vanishes $k_\Delta = 0$ and $f_\uparrow = f_\downarrow$. The spatial depen-

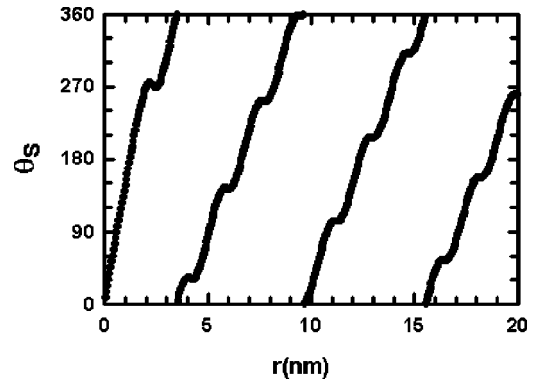


FIG. 3. The spiral angle $\theta_s(r)$ at $T = 10$ K. The chemical potential only cut across the single band of one particular spin flavor and the polarization of itinerant carriers is almost one.

dence of $J_{xy}(r)$ is also oscillatory as the diagonal parts. However, the existence of the off-diagonal exchange interaction gives rise to an interesting phenomena which is absent for usual RKKY interaction.

Suppose we sandwich DMS with two ferromagnets as shown in Fig. 1. The perpendicular polarization between DMS and the left ferromagnet could be made by utilizing the anisotropy of DMS making the hard axis of DMS parallel to the left ferromagnet. The moment on the left ferromagnet would induce magnetization in both y and x axes since the off-diagonal part is not zero. It is useful to define the spiral angle of the induced magnetic moment,

$$\tan \theta_s(r) = \frac{J_{xy}(r)}{J_{yy}(r)}. \quad (6)$$

The spatial dependencies of the spiral angle at $T = 10$ K and $T = 44$ K are plotted in Figs. 3 and 4. It is rather interesting that the induced moments through the DMS junction are characterized by both spiral rotations and angular oscillations. After some algebra, the corresponding length scales of spiral and oscillatory motions are approximately

$$\lambda_s \approx \frac{2\pi}{\sqrt{k_F^2 + k_\Delta^2 - k_F^2}}, \quad (7)$$

$$\lambda_o \approx \frac{2\pi}{\sqrt{k_F^2 + k_\Delta^2 + k_F^2}}, \quad (8)$$

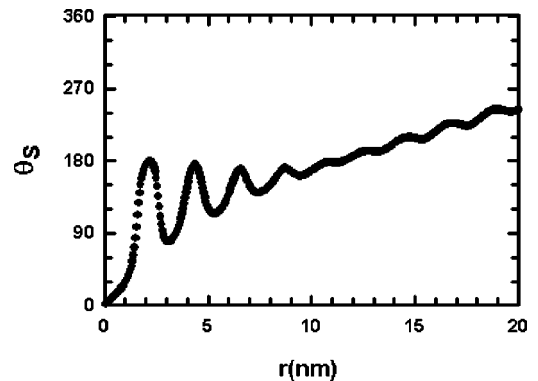


FIG. 4. The spiral angle $\theta_s(r)$ at $T = 44$ K. Both bands of different spins are almost degenerate and the spin polarization is small.

where k_F is the Fermi momentum of the unpolarized itinerant carriers.

At low temperature $T=10$ K, the chemical potential only cuts through single band and most of the itinerant carriers have the same spin orientation. The direction of the induced moment points along the direction of the spiral angle θ_s , depending on the width of the DMS junction. As is clear from Fig. 3, accompanied by spiral motion, there is also the oscillatory motion (with shorter period) which creates the wiggles in the trace. A remarkable feature is that the spiral motion does not seem to decay away as quickly as the exchange couplings $J_{xx}(r)$ and $J_{xy}(r)$ themselves. This may imply that the spiral dependence is easier to observe in experiments than the usual RKKY oscillations. Besides, the spiral-angular dependence of the induced moment also makes it charming for spin-dependent transport in tunneling magnetoresistance application and opens up a new window for new functionality of device designs.

Close to the Currie temperature $T=44$ K, both bands of the itinerant carriers are almost degenerate and the polarization is small. From Eq. (7), we expect that the period of spiral motion becomes large, as shown in Fig. 4. The oscillatory motion becomes transparent within one spiral period and decays away rapidly. While one might naively expect that the spiral motion is weakened by the small polarization, it is actually not the case. The spiral motion persists but with a longer period. As the temperature approaches the critical one, the period of the spiral motion becomes infinitely long while the oscillatory motion gets enhanced. Eventually, the spiral angle only takes on discrete values, either $\theta_s=0$ or $\theta_s=\pi$, which correspond to the ordinary RKKY oscillations. However, as long as $T < T_C$, the mediated exchange interaction is qualitatively different from that generated by unpolarized itinerant carriers.

In conclusion, we studied the exchange interactions mediated by polarized itinerant carriers in DMS junction. We found that the induced moment possesses a spiral motion accompanied by oscillatory motions. The spiral motion remains robust in the entire regime below the Curie tempera-

ture, while the angular oscillations get enhanced as the polarization becomes small. A ferromagnet/DMS/ferromagnet junction would bring out this spiral dependence and leads to interesting spin-dependent transport phenomena.

The authors are thankful for the support of the National Science Council in Taiwan through Grant Nos. NSC-91-2112-M-230-001(S.-J.S.), NSC-90-2112-M-007-050(H.-H.L.), NSC-91-2112-M-007-040(H.-H.L.), and NSC-91-2120-M-007-001(H.-H.L.). The hospitality of the National Center for Theoretical Science, where the work was initiated, is greatly acknowledged.

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